# COMPOSITION OF NATURAL ORGANIC MATERIALS AND THEIR DECOMPOSITION IN THE SOIL: IV. THE NATURE AND RAPIDITY OF DECOMPOSITION OF THE VARIOUS ORGANIC COMPLEXES IN DIFFERENT PLANT MATERIALS, UNDER AEROBIC CONDITIONS

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The rapidity of decomposition of different organic substances of either plant or animal origin in soil is controlled largely by four distinct factors:

(*a*) The chemical composition of the organic material, which, in the case of plants and plant remains, depends primarily upon the nature and age of the plant as well as upon the conditions of its nutrition. (*b*) The presence of sufficient nitrogen to enable the microorganisms bringing about the decomposition to carry out this process in the shortest possible time; in the case of nitrogen-rich plant residues, as in young plants used for green manuring purposes, or legume residues, this never becomes a limiting factor; however, in the case of plant residues poor in nitrogen, such as straw, the problem may become one of considerable importance. (*c*) The nature of microörganisms active in the decomposition processes. (*d*) The environmental conditions at which decomposition is carried out, especially aeration, moisture supply, soil reaction, and temperature.

To throw light upon these important phases of the problem of decomposition of organic residues in the soil, the following experiments were undertaken. Four different plant materials, varying distinctly in chemical composition, were selected for this purpose; namely, (*a*) mature corn stalks (and leaves); (*b*) rye straw; (*c*) mature, yellow oak leaves, freshly fallen to the ground; (*d*) mature alfalfa plants, freshly harvested.

Each of these plant materials was collected in sufficient quantity and passed separately through a chopper, which cut them into small pieces. After the moisture content of the plant material was determined, a sufficient quantity of each was added to a series of glazed earthenware pots, to give 200 to 280 gm. of dry material in each pot. Sufficient water was then added to each pot to bring the total moisture content of the compost to 66.6 per cent, or to 200 per cent moisture on the basis of the dry organic matter.

Half of the pots received a mineral solution containing 1 gm. $(NH_4)_2HPO_4$, 1 gm. $K_2HPO_4$, and 2 gm. $CaCO_3$. The nutrients thus added were far from sufficient to allow a very rapid decomposition of the nitrogen poor plant materials, such as the rye straw; at least five times as much additional nitrogen would have been required by the microörganisms for the complete decomposition of the celluloses and hemicelluloses in this plant material. All the pots

were inoculated with a suspension of fresh soil, covered with plates, and incubated at 25 to 28°C.

At intervals, the residual organic matter in each pot was weighed, the moisture content determined, and an aliquot portion taken for analysis. The results were always calculated on the basis of both the percentage of the residual material and the total original material, making thereby due allowance for the samples removed at different times for chemical analysis; the last calculation would enable one to determine just how much of the total amount of each of the different plant constituents had been decomposed in the given period of time.

Various methods have been used in the past for following the course of decomposition by microörganisms of plant material or animal residues, either in soil or in compost. These methods were usually based upon measuring only one product of decomposition, such as ammonia and frequently nitrate or carbon dioxide. The assumption was thereby made that under a definite set of conditions, the liberation of these various products of microbial metabolism runs parallel to the total decomposition of the organic residues as a whole as well as of their various constituents. This assumption is not always justified. In the case of a plant substance containing only a small amount of nitrogen, very little free ammonia or nitrate will be produced even after considerable decomposition has taken place. This is because most of the inorganic nitrogen, which becomes liberated as a result of the decomposition of the organic nitrogenous constituents of the plant substance, is reassimilated by the microörganisms; the latter utilize the energy liberated in the process of decomposition of the celluloses and hemicelluloses. Evolution of carbon dioxide is a more direct index of decomposition, although the disintegration of the same amount of cellulose will yield varying amounts of carbon dioxide when carried out by different organisms and under different conditions. Further, this method tells nothing at all as to the particular chemical complexes among the plant constituents which are undergoing decomposition. To speak of the decomposition of the plant material as a whole, as measured by the evolution of carbon dioxide, is to neglect the nature of the numerous chemical processes which are taking place thereby. Another important limitation of these methods for studying decomposition of organic matter is that little information is gained concerning the chemical nature of the residual material which results from decomposition and which goes to increase the "humus" ccntent of the soil.

Attempts have been made in some instances to measure the decomposition of plant material either by determining the total reduction in the bulk of the organic matter or by measuring the disappearance of one of the important constituents. However, the mere fact that 40, 60, or 80 per cent of the organic matter of the specific plant material has disappeared, under certain conditions of decomposition and in a definite period of time, supplies no in-

formation whatsoever concerning the chemical changes that have taken place in the various constituents.

Studies dealing with the disappearance of specific chemical complexes in the organic material undergoing decomposition have been limited largely to the celluloses and hemicelluloses. Barthel and Bengtsson (2) have shown that the decomposition of celluloses in plant residues depends upon the nature of the plant and upon the amount of available nitrogen. Cellulose in the stubble and roots of legumes decomposed more slowly than did cellulose in the roots of cereal straws. This was explained by the greater content of nitrogen-free, non-cellulosic, carbonaceous materials in the former than in the latter. Fraps (5) observed that, as a result of decomposition of different plant materials in soil for a period of eight weeks, there were left 7 per cent of the pentosan in cotton seed meal, 31 per cent of the pentosan in Sudan grass, 61 per cent of the pentosan in rice bran, and 75 per cent of the pentosan in sheep manure. These results point definitely to differences in the decomposition of the same group of organic complexes in different plant materials.

Schmidt, Peterson, and Fred (11) found that when corn fodder and rye straw were undergoing decomposition under the same conditions, the former lost 50 per cent of its pentosans in 100 days and the latter only 35 per cent in 300 days; they also observed that common fungi synthesize pentosans, even in media free from pentose material. According to Rege (9), 80 per cent of the pentosan in fresh rye straw, when the straw is allowed to decompose under favorable conditions, disappeared in 40 days; in fact during the early period of decomposition, that is between the fourth and eighth days, practically all the loss in dry matter was accounted for almost entirely by the loss of pentosan.

Very few attempts have been made to measure the rate of disappearance of the various chemical complexes in the decomposing plant materials. The investigations of Egorov (6), Bach (1), and König (7) can be summarized as follows: During the early stages of decomposition of plant materials in soil or in compost, the pentosans disappear more rapidly than do the total organic constituents of the material, and even more rapidly than do the celluloses. After considerable decomposition has taken place, the celluloses are found to disappear more quickly than the hemicelluloses (including the pentosans). The rate of decomposition of both hemicelluloses and celluloses is greater than that of the total organic matter, as shown by the amount of residual material. Organic nitrogenous compounds tend to accumulate, especially in the case of nitrogen-poor organic residues, so that the total protein content of the residual undecomposed material diminishes only slowly when compared with the rate of disappearance of the total organic matter. Lignins seem to be resistant to decomposition, more so than any other group of the major plant constituents; they are found, therefore, to accumulate in the process of decomposition of plant residues, with certain few exceptions.

Bach (1) found that when stable manure is added to the soil and allowed to decompose, the per cent of carbon in the residual organic matter increases

from an initial 47 to 51 per cent to 58 per cent. This was explained by the fact that the celluloses and pentosans originally present in the fresh manure contained 44.44 and 45.44 per cent of carbon respectively, while the lignins and cutins contained 67.31 to 71.35 per cent of carbon. As a result of decomposition, the celluloses and pentosans disappear rapidly while the lignins and cutins accumulate, thus leading to a gradual increase in carbon content.

Rose and Lisse (10), analyzing wood at different stages of decomposition, and Bray and Andrews (3) working with pure cultures of fungi, also demonstrated that, in the decomposition of wood by various Hymenomycetes, the pentosans and celluloses are first to disappear, whereas the lignins are practically resistant to decomposition. Only very few fungi, namely those causing the "white rots," are capable of decomposing lignins as well as celluloses (4). The common wood-destroying fungus *Merulius lacrymans* decomposes the celluloses while the lignins are left; these are converted partly into depolymerized and split substances of a "humin-like" nature.

It has also been found that, as a result of the decomposition of plant substances there is a marked increase in the alkali-soluble material of the undecomposed or accumulated residues. The tendency has been to explain this phenomenon either by a modification of the lignin molecule, making it more readily soluble in alkali, or by the formation of some intermediary products of cellulose decomposition soluble in alkalies.

Waksman and Tenney (14) came to the conclusion, as a result of studies on the decomposition of the rye plant harvested at different stages of growth, that the water-soluble organic substances are first to be decomposed in the soil by microörganisms. This is soon followed by an attack upon the pentosans and at the same time, or immediately after, upon the celluloses. Although the plant residues contain a larger amount of celluloses than of hemicelluloses and although the latter begin to undergo decomposition sooner than the former, the celluloses disappear sooner and more completely than the hemicelluloses. This was explained by the fact that, whereas pentosans may be attacked more quickly and by a greater variety of microörganisms than celluloses, other hemicelluloses (galactans, mannans) may be more resistant; further, as a result of the growth of microörganisms upon the plant residues, considerable quantities of hemicelluloses are synthesized in the form of bacterial and fungus slimes and gums. The lignins were found to be more resistant to decomposition and tend to accumulate in the soil. The plant proteins are readily decomposed, but very little nitrogen becomes liberated in the soil as ammonia, as long as there is left a considerable amount of undecomposed cellulose and pentosan. Accompanying the decomposition of these carbohydrates, considerable synthesis of microbial proteins takes place. This synthesis is also a result of the growth of the microörganisms bringing about the decomposition of the organic matter.

The dark residues resulting from the decomposition of the plant material, or the so-called "humus" tends to have the following composition: a large

amount of lignins or modified lignins of plant origin; a large amount of protein of microbial origin; a fairly high hemicellulose content, partly of plant and partly of microbial origin; small amounts of plant constituents still undergoing decomposition, such as celluloses and ether-soluble substances; small amounts of other synthesized microbial products, some of which are undergoing decomposition, as various fatty substances, chitinous materials and nitrogenous complexes.

An attempt will be made in this paper to elucidate the problem of decomposition of different plant materials under aerobic conditions, to establish the relation between the different organic plant constituents in the process of

TABLE 1

*Proximate composition of plant materials used for decomposition studies*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | CORN STALKS | RYE STRAW | OAK LEAVES | ALFALFA PLANTS |
|---|---|---|---|---|
| Ether-soluble fraction | 1.80 | 1.84 | 3.71 | 2.75 |
| Cold-water-soluble | 10.58 | 4.51 | 8.28 | 12.44 |
| (Reducing sugar) | (6.00) | (0.88) | (2.73) | (1.31) |
| Hot-water-soluble | 3.56 | 1.75 | 5.65 | 4.80 |
| (Alcohol-soluble*) | (4.19) | (3.49) | (5.92) | (7.66) |
| Hemicelluloses | 17.63 | 21.10 | 12.93 | 8.52 |
| Celluloses | 29.67 | 38.62 | 13.78 | 26.71 |
| Lignins | 11.28 | 14.63 | 30.30 | 10.78 |
| Crude protein | 1.98 | 0.81 | 4.25 | 8.13 |
| (Total nitrogen) | (0.66) | (0.24) | (0.77) | (2.58) |
| Ash | 7.53 | 4.18 | 5.09 | 10.30 |

* The alcohol-soluble fraction was determined on a separate sample. In view of the fact that this fraction was not determined in the decomposed material, it is left out of further consideration; it is given here, however, merely for the purpose of comparison.

decomposition, and to throw further light upon the rôle of microörganisms in the processes of decomposition and synthesis.

It is quite essential, in a study of this nature, to be able to make as complete an analysis of the organic plant constituents as possible. Such an analysis has been proposed elsewhere (12) and was used to considerable advantage for determining the proximate composition of various plant materials. It was found that, by this method of analysis, 85 to 96 per cent of the plant constituents (except in the case of mosses) could be accounted for. No attempt has been made to measure those complexes which occur in the plant in concentrations of less than one per cent.

The following organic complexes are accounted for in this method:

(*a*) cold-water-soluble substances, including the sugars and amino acids; (*b*) hot-water-soluble substances, including starches, pectins, tannins, and uric acid; (*c*) hemicelluloses, determined by hydrolysis with hot dilute mineral acid and measured in the form of reducing

sugars; (*d*) celluloses, determined by hydrolysis with cold 80 per cent sulfuric acid followed by boiling for several hours, after diluting with 15 volumes of water; (*e*) lignins, as determined by their insolubility in cold 80 per cent sulfuric acid, with ash and nitrogen accounted for; (*f*) ether-soluble substances, including fats and waxes; (*g*) crude proteins.

In view of the fact that the alcohol-soluble fraction is not included in the following analyses, the results will be short 3.5 to 7.5 per cent of the plant constituents. However, since the same method has been used in the analysis of both the fresh material and the decomposed residues, the results are found to be comparable. The proximate chemical composition of the four materials used in the following investigations is given in table 1. The corn stalks were harvested when mature but not fully dry, some of the leaves being still green. The rye straw was in a fully mature stage, as shown by the low nitrogen

TABLE 2

*Chemical composition of corn stalks and decomposed residue at different stages of decomposition, without the addition of nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | | |
|---|---|---|---|---|---|
| | | 27 | 68 | 205 | 405 |
| Ether-soluble | 1.80 | 1.97 | 0.96 | 0.78 | 0.35 |
| Cold-water-soluble | 10.58 | 3.37 | 5.74 | 2.80 | 4.28 |
| Hot-water-soluble | 3.56 | 2.50 | 3.02 | 4.11 | 9.19 |
| Hemicelluloses | 17.63 | 16.34 | 15.93 | 15.35 | 10.74 |
| Celluloses | 29.67 | 26.36 | 22.50 | 13.39 | 4.78 |
| Lignins | 11.28 | 18.26 | 19.66 | 23.44 | 23.86 |
| Crude protein | 1.98 | 4.37 | 4.69 | 9.00 | 12.97 |
| Ash | 7.53 | ..... | ..... | 19.16 | 26.63 |

content. The oak leaves were also mature and recently fallen; they were collected from the surface of ground under the trees. The alfalfa plants were freshly harvested in the fall of the year.

Attention should be called to the fact that the crude protein figures indicate the total nitrogen minus the water-soluble nitrogen, the difference being multiplied by 6.25. The total nitrogen figures are given separately.

## DECOMPOSITION OF CORN STALKS

The corn stalks contained 66 per cent moisture when harvested, showing that they were not as yet fully mature. The material was air-dried and subjected to a detailed chemical analysis, the results of which are given in table 1. For the study of aerobic decomposition, the fresh material was cut up immediately and used without preliminary drying. In view of the fact that the moisture content of the fresh material was just sufficient for optimum aerobic decomposition, no more water was added. The analysis of the dry material shows that it contained 10.58 per cent of organic substances soluble

in cold water. More than half of this, namely 6 per cent, was in the form of reducing sugars. This high concentration of sugar explains the rapid initial decomposition of the corn stalks. Out of the 0.66 per cent total nitrogen in the dry material, 0.26 per cent, or nearly 40 per cent of the total nitrogen,

TABLE 3

*Chemical composition of corn stalks and the decomposed residue at different stages of decomposition, in the presence of added nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | | |
|---|---|---|---|---|---|
| | | 27 | 68 | 205 | 405 |
| Ether-soluble | 1.80 | 2.22 | 0.80 | 0.64 | 0.25 |
| Cold-water-soluble | 10.58 | 3.43 | 5.27 | 3.96 | 4.59 |
| Hot-water-soluble | 3.56 | 2.45 | 3.20 | 5.36 | 8.71 |
| Hemicelluloses | 17.63 | 15.56 | 16.41 | 10.68 | 10.39 |
| Celluloses | 29.67 | 23.80 | 21.93 | 6.28 | 5.05 |
| Lignins | 11.28 | 17.70 | 19.12 | 23.83 | 21.30 |
| Crude protein | 1.98 | 4.81 | 6.84 | 10.93 | 12.13 |
| Ash | 7.53 | ..... | ..... | 26.12 | 29.43 |

TABLE 4

*Total decomposition of the various organic chemical constituents of corn stalks, without the addition of nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | MATERIAL LEFT AFTER DAYS OF DECOMPOSITION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 27 | | 68 | | 205 | | 405 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | *gm.* | *gm.* | | *gm.* | | *gm.* | | *gm.* | |
| Total dry material | 203.00 | 129.00 | 63.54 | 92.50 | 45.60 | 59.50 | 29.30 | 41.20 | 20.30 |
| Ether-soluble fraction | 3.65 | 2.54 | 69.59 | 0.89 | 24.38 | 0.46 | 12.60 | 0.14 | 3.84 |
| Cold-water-soluble organic matter | 21.48 | 4.35 | 20.25 | 5.31 | 24.72 | 1.67 | 7.77 | 1.76 | 8.19 |
| Hot-water-soluble organic matter | 7.23 | 3.23 | 44.67 | 2.79 | 38.59 | 2.45 | 33.89 | 3.79 | 52.42 |
| Hemicelluloses | 35.79 | 21.09 | 58.93 | 14.74 | 41.18 | 9.13 | 25.51 | 4.42 | 12.35 |
| Celluloses | 60.24 | 34.00 | 56.44 | 20.81 | 34.55 | 7.97 | 13.23 | 1.97 | 3.27 |
| Lignins | 22.90 | 23.56 | 102.88 | 18.19 | 79.43 | 13.95 | 60.92 | 9.83 | 42.93 |
| Crude protein | 4.01 | 5.64 | 140.65 | 4.34 | 108.23 | 5.36 | 133.67 | 5.34 | 133.17 |

was in a water-soluble form. These facts, as well as the low lignin content of the corn stalks, account for the rapid disappearance of most of the organic constituents in their decomposition, especially in the presence of a small amount of inorganic salts of nitrogen, phosphorus, and potassium.

Tables 2 and 3 give the chemical composition of the corn stalks, with and

without the additional nutrients, at different stages of decomposition. Tables 4 and 5 show the amount of total decomposition that the various organic chemical constituents have undergone, in the absence and in the presence of added nutrient salts, as shown by the concentrations of the various groups left at the different periods of incubation. These figures were obtained by multiplying the total residual material (on a dry basis and after allowance has been made for the samples removed) by the percentage composition.

Figures 1 and 2 illustrate the rapidity of transformation of the most important groups of organic plant complexes, in the process of decomposition of corn stalks, with and without additional nutrient salts. The left hand columns represent the abundance of the particular complex in the original undecom-

TABLE 5

*Total decomposition of the various organic chemical constituents of corn stalks in the presence of added nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | MATERIAL LEFT AFTER DAYS OF DECOMPOSITION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 27 | | 68 | | 205 | | 405 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | *gm.* | *gm.* | | *gm.* | | *gm.* | | *gm.* | |
| Total dry material | 203.00 | 107.30 | 52.86 | 83.20 | 41.00 | 53.80 | 26.50 | 45.70 | 22.50 |
| Ether-soluble fraction | 3.65 | 2.38 | 65.21 | 0.67 | 18.36 | 0.34 | 9.32 | 0.11 | 3.01 |
| Cold-water-soluble organic matter | 21.48 | 3.67 | 17.09 | 4.38 | 20.39 | 2.13 | 9.92 | 2.10 | 9.78 |
| Hot-water-soluble organic matter | 7.23 | 2.62 | 36.24 | 2.66 | 36.79 | 2.88 | 39.83 | 3.98 | 55.05 |
| Hemicelluloses | 35.79 | 16.65 | 46.52 | 13.65 | 38.14 | 5.75 | 16.07 | 4.75 | 13.27 |
| Celluloses | 60.24 | 25.46 | 42.26 | 18.25 | 30.30 | 3.38 | 5.61 | 2.31 | 3.83 |
| Lignins | 22.90 | 18.94 | 82.71 | 15.91 | 69.48 | 12.82 | 55.98 | 9.73 | 42.49 |
| Crude protein | 4.01 | 5.16 | 128.68 | 5.69 | 141.90 | 5.88 | 146.63 | 5.54 | 138.15 |

posed plant material, on the basis of 100 per cent. The second column to the right of it represents the concentration, in per cent, of the particular complex at the time of the first sampling, namely after 27 days; the third, fourth, and fifth columns to the right represent the concentrations of the particular complex at the second, third, and fourth sampling; namely, after 68, 205, and 405 days, respectively.

Both the tables and figures give a fair idea of the processes which have been taking place in the decomposition of corn stalks under aerobic conditions. The addition of inorganic nutrients exerted a decidedly favorable effect upon the early stages of decomposition of the total organic matter, especially of the celluloses and hemicelluloses. After 27 days, 36.5 per cent of the total organic constituents of the corn stalks disappeared in the absence of the additional salts and 47.1 per cent in their presence; 41 per cent of the hemi-

celluloses and 43.6 per cent of the celluloses were decomposed in the absence of added nutrients, whereas, in their presence, the disappearance of these two groups of complexes was 53.5 and 57.7 per cent respectively. These results induce certain important conclusions: 1. The addition of available nitrogen was responsible for a greater decomposition of the celluloses and hemicelluloses in the corn stalks, especially during the early stages of decomposition. 2. Both the hemicelluloses and the celluloses disappeared more quickly than the total organic matter; this indicates either that synthesis of new complexes has taken

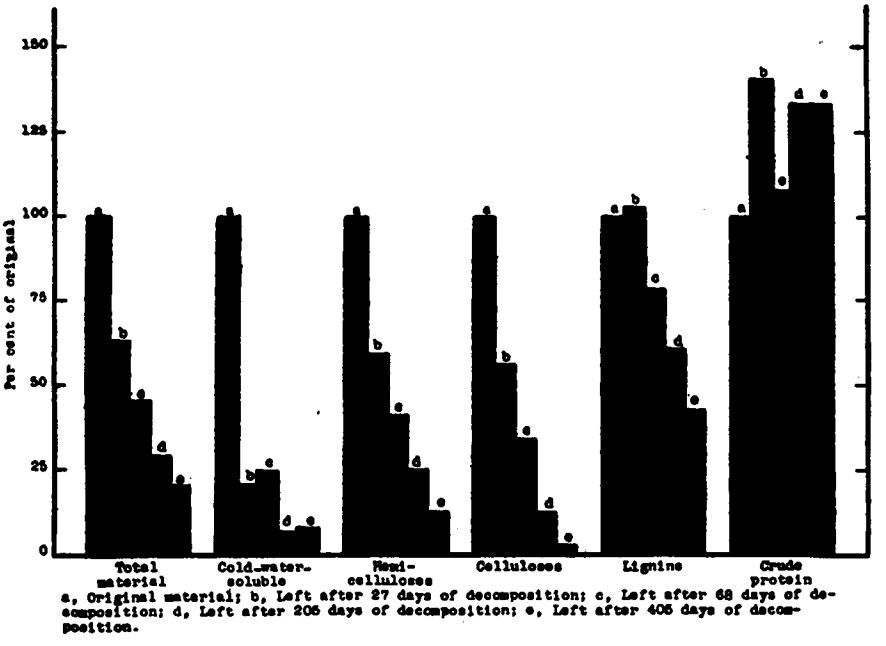


FIG. 1. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF CORN STALKS WITHOUT ADDITIONAL NUTRIENT SALTS

place or that some of the more resistant plant complexes have accumulated. Both assumptions are correct, as is shown later.

The favorable effect of additional inorganic nutrients upon decomposition is still marked after 68 days of decomposition, but this effect tends to disappear later. It is interesting to note also that at the beginning of decomposition the hemicelluloses decomposed as rapidly as if not more so than the celluloses; however, during the latter stages, the celluloses disappeared rapidly, while appreciable quantities of hemicellulose were still left in the residual compost.

The cold-water-soluble substances tend to disappear rapidly when decomposition sets in. The hot-water-soluble constituents decompose more slowly and even tend to accumulate during the later stages of decomposition, no

doubt because of the production of synthesized microbial cell substance containing substances soluble in hot water. The fats and oils, or the ether-soluble substances, of the corn stalks were also rapidly decomposed under aerobic conditions.

The lignins and the proteins are the two important complexes among the various organic plant constituents which tend to accumulate. The reason for their accumulation, however, is not the same in both cases. The lignins are more resistant to attack by microörganisms than are the other groups of plant constituents, such as the celluloses, hence they accumulate as the decomposition

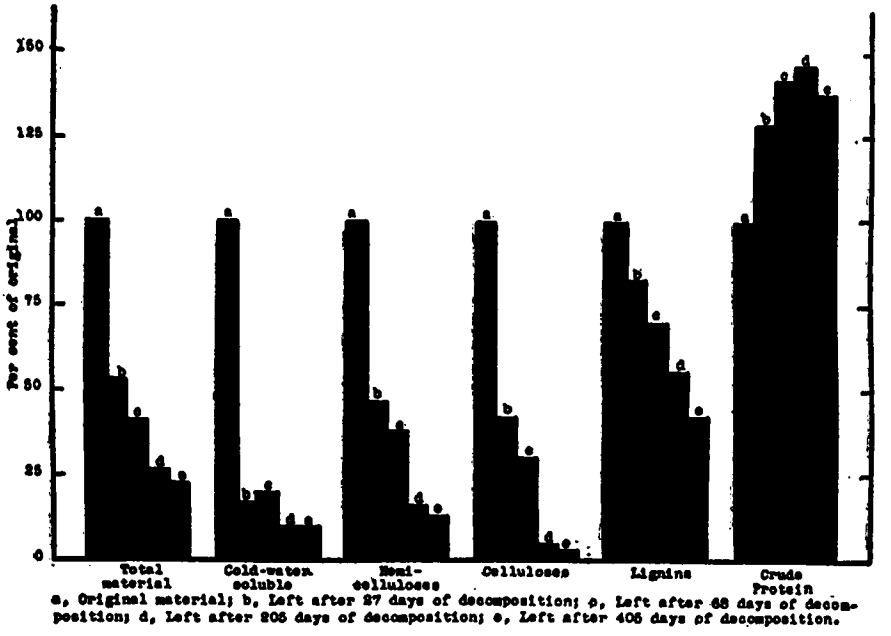


FIG. 2. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF CORN STALKS WITH ADDITIONAL NUTRIENT SALTS

of the more readily available complexes proceeds further. In 27 days, only a small fraction of the lignins of the corn stalks undergoing decomposition under aerobic conditions has disappeared; this accounts for the increasing concentration of the lignin content of the residual material. The original plant substance had only 11.28 per cent lignin; the material decomposed for 405 days contained twice as much lignin in proportion to the other constituents. However, there was no absolute preservation of the lignin complex, as assumed by some investigators. Under aerobic conditions, the lignins gradually decompose, not so rapidly by far as the other chemical complexes, but still in a very definite manner; after 405 days, 57.5 per cent of the lignin in the corn stalks has actually disappeared. Under anaerobic conditions, the

lignins are preserved to a much greater extent, as will be shown in a later contribution.

These results as well as those obtained on the decomposition of the other three plant materials prove definitely that lignins decompose under aerobic conditions. So far no definite explanation can be submitted concerning the nature of the microörganisms active in this process. It is known that certain *Basidiomycetes* are capable of decomposing lignins in the rotting of trees. It is also known that lignins disappear partly when digested by animals; the limited evidence points to actinomyces as possible agents in the decomposition of lignins. Whether one of these three groups of organisms was responsible for the disappearance of some of the lignins in the decomposition studies reported here or all three groups of organisms took a part in the process still remains to be established.

TABLE 6

*Nitrogen transformation in the decomposition of corn stalks*

In per cent of total residual material

| FORM OF NITROGEN | NO ADDITIONAL NITROGEN | | | | | AMMONIUM PHOSPHATE ADDED | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Incubation | | | | | Incubation | | | | |
| | 0 days | 27 days | 68 days | 205 days | 405 days | 0 days | 27 days | 68 days | 205 days | 405 days |
| Total nitrogen | 0.66 | 0.95 | 1.02 | 1.70 | 2.44 | 0.76 | 1.05 | 1.37 | 2.10 | 2.34 |
| Soluble in cold water | 0.25 | 0.13 | 0.14 | 0.13 | 0.12 | 0.35 | 0.16 | 0.14 | 0.14 | 0.14 |
| Soluble in hot water | 0.09 | 0.12 | 0.13 | 0.13 | 0.25 | 0.09 | 0.13 | 0.14 | 0.21 | 0.26 |
| Hydrolizable by 2 per cent HCl | 0.13 | 0.23 | 0.36 | .... | 0.92 | 0.13 | 0.28 | 0.39 | .... | 0.93 |
| "Humin" nitrogen, not acted upon by autoclaving with 6 per cent $H_2SO_4$ | 0.13 | 0.24 | 0.33 | 0.44 | 0.51 | 0.13 | 0.27 | 0.33 | 0.51 | 0.51 |

The increase in the crude protein (insoluble in cold and hot water) with the advance of decomposition of the corn stalks was not only relative to the other plant constituents, but there was an actual total increase in the amount of protein, due to the transformation of the water-soluble nitrogen compounds into insoluble complex organic nitrogenous substances. The greatest increase in the protein content was obtained in those preparations which received inorganic nitrogen salts. The reasons for the increase in the protein as a result of decomposition of nitrogen-poor organic plant residues have been expounded in detail elsewhere (15). These results throw further light upon the problem of synthesis of new protein material as a result of the activities of the microörganisms which bring about the decomposition of the celluloses and hemicelluloses. The fact that, in the absence of additional nitrogen, the increase in the amount of crude protein took place at the expense of the water-soluble simple nitrogenous compounds is brought out in table 6. Although the total nitrogen of the residual material rapidly increased with the advance

in decomposition, the water-soluble nitrogen decreased. The acid hydrolizable nitrogen increased even more rapidly than the total nitrogen. It is interesting to record the marked increase in the so-called "humin" nitrogen or that part of the nitrogen which is found in the lignin fraction. These results point definitely to the building up of resistant nitrogenous complexes by the microörganisms.

As the water-soluble and insoluble nitrogenous compounds, first in the form of plant constituents then as constituents of microbial cells undergoing decomposition, are repeatedly hydrolized and resynthesized by microörganisms, more and more of the resistant nitrogenous complexes are produced. These are attacked less and less readily, and finally become incorporated in the residual material equivalent to the soil "humus" with its large content of organic nitrogenous complexes resistant to decomposition.

TABLE 7

*Chemical composition of rye straw and its decomposition products at different stages of decomposition, without the addition of nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | |
|---|---|---|---|---|
| | | 66 | 143 | 386 |
| Ether-soluble | 1.84 | 1.05 | 1.33 | 1.62 |
| Cold-water-soluble | 4.51 | 2.12 | 2.45 | 1.75 |
| Hot-water-soluble | 1.75 | 2.19 | 2.23 | 2.08 |
| Hemicelluloses | 21.10 | 19.81 | 21.25 | 18.18 |
| Celluloses | 38.52 | 35.33 | 33.47 | 30.38 |
| Lignins | 14.63 | 17.53 | 17.59 | 18.88 |
| Crude protein | 0.81 | 1.69 | 1.88 | 2.76 |
| Ash | 4.18 | 5.50 | 5.60 | 5.72 |

## DECOMPOSITION OF RYE STRAW

The chemical composition of the rye straw used in these decomposition studies varied in several respects from that of the corn stalks. The straw had much less water-soluble material, much less nitrogen, but a larger proportion of celluloses, hemicelluloses, and lignins. One would expect from this analysis that the decomposition of the straw should proceed at a much slower rate than that of the corn stalks. This was actually found to be the case.

The straw, undergoing decomposition under the same conditions as the corn stalks, was analyzed only three times; namely, after 66, 143, and 386 days incubation at 25–28°C. Tables 7 and 8 give the chemical composition of the straw without and with the same additional inorganic salts at different stages of decomposition. Tables 9 and 10 and figures 3 and 4 give the total corresponding amounts of the different chemical complexes of the fresh and decomposed material at the different stages of decomposition.

In comparison with the corn stalks, the rye straw was found to decompose very slowly. Although the nature and course of decomposition of the straw are similar to that of the corn product, the amount decomposed is considerably less. At the end of 386 days, nearly three times as much organic matter was left from the straw as from the corn stalks. This is due largely

TABLE 8

*Chemical composition of rye straw and its decomposition products at different stages of decomposition, in the presence of added nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | |
|---|---|---|---|---|
| | | 66 | 143 | 386 |
| Ether-soluble | 1.84 | 0.92 | 1.14 | 0.59 |
| Cold-water-soluble | 4.51 | 2.05 | 2.21 | 1.76 |
| Hot-water-soluble | 1.75 | 1.89 | 1.81 | 1.80 |
| Hemicelluloses | 21.10 | 19.61 | 21.10 | 17.98 |
| Celluloses | 38.62 | 33.58 | 31.02 | 25.99 |
| Lignins | 14.63 | 18.10 | 18.28 | 18.43 |
| Crude protein | 0.81 | 2.25 | 2.38 | 3.53 |
| Ash | 4.18 | 6.50 | 6.50 | 8.00 |

TABLE 9

*Total decomposition of the various organic constituents of rye straw, without the addition of nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | ORGANIC MATTER LEFT, AFTER DAYS OF DECOMPOSITION | | | | | |
|---|---|---|---|---|---|---|---|
| | | 66 | | 143 | | 386 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | gm. | gm. | | gm. | | gm. | |
| Total dry material | 277.00 | 230.00 | 83.03 | 197.00 | 71.12 | 171.00 | 61.73 |
| Ether-soluble fraction | 5.10 | 2.42 | 47.45 | 2.62 | 51.37 | 2.77 | 54.31 |
| Cold-water-soluble organic matter | 12.49 | 4.88 | 39.07 | 4.83 | 38.67 | 2.99 | 23.94 |
| Hot-water-soluble organic matter | 4.85 | 5.04 | 103.92 | 4.39 | 90.52 | 3.56 | 73.40 |
| Hemicelluloses | 58.42 | 45.56 | 77.99 | 41.86 | 71.65 | 31.09 | 53.22 |
| Celluloses | 106.66 | 81.25 | 76.18 | 65.94 | 61.82 | 51.95 | 48.71 |
| Lignins | 40.51 | 40.32 | 99.53 | 34.65 | 85.53 | 32.28 | 79.68 |
| Crude protein | 2.25 | 3.88 | 172.44 | 3.70 | 164.44 | 4.72 | 209.78 |

to the insufficient decomposition of the celluloses and hemicelluloses in the straw: at the end of 405 days there was left in the case of the corn stalks 3.27–3.83 per cent of the celluloses and 12.35–13.27 per cent of the hemicelluloses; however, in the case of the straw, there was left, at the end of practically the same period of time (386 days) 37.28–48.71 per cent of the celluloses and 47.09 to 53.22 per cent of the hemicelluloses present in the original material.

The lack of available nitrogen was chiefly responsible for the slow decomposition of the rye straw, especially of the celluloses and hemicelluloses. The amount of inorganic nitrogen added to some of the pots was not sufficient to produce conditions most favorable for decomposition of the straw. It resulted only in a somewhat greater reduction of both groups of carbohydrates than in the straw not receiving any additional available nitrogen.

Here also the lignins proved to be more resistant to decomposition than the other constituents of the straw. Likewise, the reduction in total organic matter was less than the decrease of celluloses and hemicelluloses. The total organic matter was reduced by 38.3 per cent in the absence of additional nitrogen and by 44.8 per cent in its presence. However, the celluloses were reduced by 51.3 and 62.7 per cent and the hemicelluloses by 46.8 and 52.9

TABLE 10

*Total decomposition of the various organic chemical constituents of rye straw, in the presence of added nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | ORGANIC MATTER LEFT, AFTER DAYS OF DECOMPOSITION | | | | | |
|---|---|---|---|---|---|---|---|
| | | 66 | | 143 | | 386 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | gm. | gm. | | gm. | | gm. | |
| Total dry material | 277.00 | 221.00 | 79.78 | 170.00 | 61.37 | 153.00 | 55.23 |
| Ether-soluble-fraction | 5.10 | 2.03 | 39.80 | 1.94 | 38.04 | 0.90 | 17.65 |
| Cold-water-soluble organic matter | 12.49 | 4.53 | 36.27 | 3.76 | 30.10 | 2.69 | 21.54 |
| Hot-water-soluble organic matter | 4.85 | 4.18 | 86.19 | 3.08 | 63.51 | 2.75 | 56.70 |
| Hemicelluloses | 58.42 | 43.34 | 74.19 | 35.87 | 61.40 | 27.51 | 47.09 |
| Celluloses | 106.66 | 74.21 | 69.58 | 52.73 | 49.44 | 39.76 | 37.28 |
| Lignins | 40.51 | 40.00 | 98.74 | 31.08 | 76.72 | 28.20 | 69.61 |
| Crude protein | 2.25 | 4.97 | 220.88 | 4.05 | 180.00 | 5.40 | 240.00 |

per cent respectively. In other words, these two groups of carbohydrates, which make up 60 per cent of the total constituents of the straw, diminished to a considerably greater extent than did the total organic matter. This reduction was balanced by the greater resistance of the lignins to decomposition and by the building up of protein material, a phenomenon already observed as a result of decomposition of the corn stalks.

Because of the comparatively greater abundance of available carbohydrates (celluloses and hemicelluloses), the microörganisms have brought about in the case of the rye straw even a greater proportional increase in the protein content than that which resulted from the decomposition of the corn stalks. This increase was naturally more marked in the presence of additional available nitrogen. The actual increase in the protein content of the residual material was 100 and 140 per cent, without and with the addition of nitrogen, respectively. The increase in the protein content of the decomposing straw

without additional inorganic nitrogen is found to be largely at the expense of the water-soluble nitrogen compounds, which were thereby made water-insoluble. This is brought out in table 11. With the progress of decomposition, there was a gradual decrease of the nitrogen soluble in cold water and a corresponding increase in the nitrogen hydrolizable by dilute hydrochloric acid and in the more resistant or so-called "humin" nitrogen, pointing to the building up by microörganisms of proteins and other complex organic nitrogenous compounds. Practically all the nitrogen was recovered in the residual

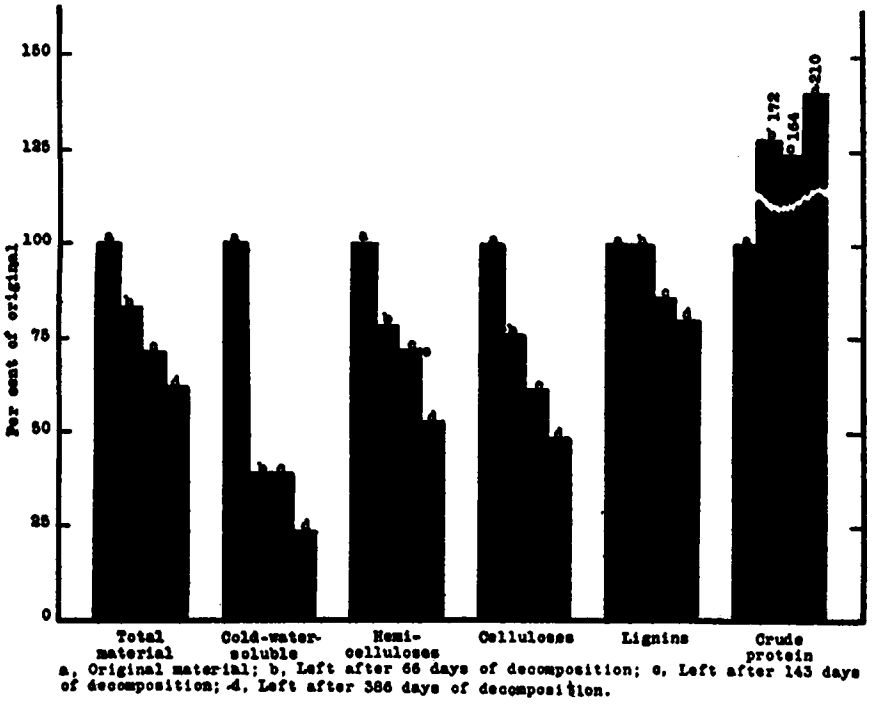


FIG. 3. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF RYE STRAW WITHOUT ADDITIONAL NUTRIENT SALTS

material, pointing to three interesting considerations: (*a*) there is no loss in nitrogen, either by volatilization or reduction processes, as long as there is sufficient available energy for the activities of microörganisms; (*b*) there is no gain in nitrogen, through processes of non-symbiotic fixation, when only celluloses and hemicelluloses are available as sources of energy even in the presence of numerous cellulose-decomposing organisms; (*c*) at least some of the nitrogenous compounds synthesized by the microörganisms are only slowly available sources of nitrogen for soil microörganisms, otherwise the celluloses and hemicelluloses would have undergone a much more rapid decomposition.

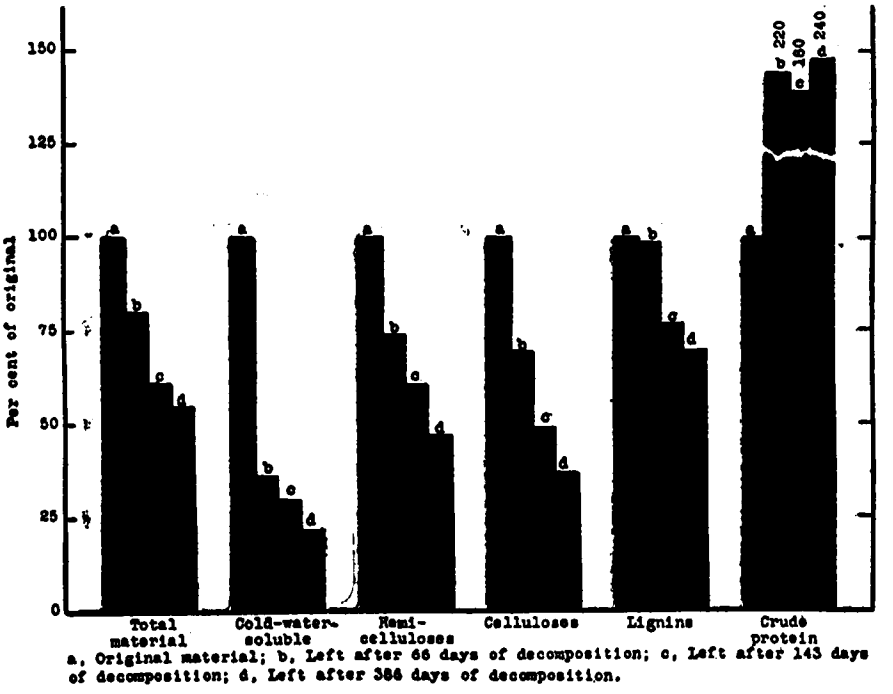


FIG. 4. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF RYE STRAW WITH ADDITIONAL NUTRIENT SALTS

TABLE 11

*Nitrogen transformation in the decomposition of rye straw*

In per cent of total material

| FORM OF NITROGEN | NO ADDITIONAL NITROGEN | | | | AMMONIUM PHOSPHATE ADDED | | | |
|---|---|---|---|---|---|---|---|---|
| | Incubation | | | | Incubation | | | |
| | 0 days | 66 days | 143 days | 386 days | 0 days | 66 days | 143 days | 386 days |
| Total nitrogen | 0.24 | 0.33 | 0.39 | 0.50 | 0.31 | 0.42 | 0.47 | 0.64 |
| Soluble in cold water | 0.11 | 0.03 | 0.05 | 0.02 | 0.18 | 0.03 | 0.05 | 0.02 |
| Soluble in hot water | 0 | 0.03 | 0.04 | 0.04 | 0 | 0.03 | 0.05 | 0.05 |
| Hydrolizable by 2 per cent HCl | 0.04 | 0.08 | 0.10 | .... | 0.04 | 0.12 | 0.14 | .... |
| "Humin" nitrogen, not acted upon by autoclaving with hot 6 per cent $H_2SO_4$ | 0.06 | 0.10 | 0.13 | .... | 0.06 | 0.10 | 0.14 | .... |

## DECOMPOSITION OF OAK LEAVES

The mature oak leaves were distinctly different in chemical composition from the corn stalks and the rye straw. The leaves were characterized by a high content of fats and waxes (ether-soluble fraction), a very high lignin (and

cutin) content, and were rich in materials soluble in hot water (tannins). On the other hand, the celluloses and hemicelluloses were not very abundant in the leaves. Their nitrogen content was higher than that of either the corn stalks or the straw. One would expect, therefore, that the leaves should show a decided difference in the nature and rapidity of decomposition from that of the two plant materials previously reported.

TABLE 12

*Chemical composition of mature oak leaves at different stages of decomposition, without the addition of nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | |
|---|---|---|---|---|
| | | 66 | 143 | 386 |
| Ether-soluble | 3.71 | 3.53 | 2.82 | 1.77 |
| Cold-water-soluble | 8.28 | 2.02 | 1.15 | 1.69 |
| Hot-water-soluble | 5.65 | 3.91 | 2.15 | 2.16 |
| Hemicelluloses | 12.93 | 12.10 | 13.03 | 12.27 |
| Celluloses | 13.78 | 11.78 | 10.41 | 8.92 |
| Lignins | 30.30 | 40.02 | 42.65 | 44.50 |
| Crude protein | 4.25 | 6.00 | 6.13 | 7.44 |
| Ash | 5.09 | 6.50 | 6.90 | 8.12 |

TABLE 13

*Chemical composition of mature oak leaves at different stages of decomposition, with the addition of nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | |
|---|---|---|---|---|
| | | 66 | 143 | 386 |
| Ether-soluble | 3.71 | 2.65 | 1.74 | 0.67 |
| Cold-water-soluble | 8.28 | 1.60 | 1.44 | 2.86 |
| Hot-water-soluble | 5.65 | 3.10 | 2.04 | 2.44 |
| Hemicelluloses | 12.93 | 12.59 | 13.27 | 13.25 |
| Celluloses | 13.78 | 11.90 | 10.94 | 9.23 |
| Lignins | 30.30 | 40.40 | 40.55 | 40.35 |
| Crude protein | 4.25 | 6.62 | 6.88 | 8.25 |
| Ash | 5.09 | 8.00 | 9.00 | 10.33 |

The chemical composition of the oak leaves at different stages of decomposition is given in tables 12 and 13, and the actual concentration of the different organic chemical complexes which have undergone decomposition is recorded in tables 14 and 15 and figures 5 and 6. In the case of this plant material as well, half of the pots received inorganic salts including nitrogen and half did not. The composts of oak leaves were allowed to incubate under the same conditions as the other two plant materials and analyzed after 66, 143, and 386 days.

The results show that although the leaves contained more nitrogen (0.77 per cent) than did the corn stalks, their decomposition was considerably slower. It was similar to that of the rye straw, which contained only about one-third or less of the nitrogen content of the leaves. These differences in the rate

TABLE 14

*Total decomposition of the various organic constituents in mature oak leaves, without the addition of nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | ORGANIC SUBSTANCES LEFT, AFTER DAYS OF DECOMPOSITION | | | | | |
|---|---|---|---|---|---|---|---|
| | | 66 | | 143 | | 386 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | gm. | gm. | | gm. | | gm. | |
| Total dry material | 223.00 | 173.00 | 77.58 | 158.00 | 70.85 | 129.00 | 57.85 |
| Ether-soluble fraction | 8.27 | 6.11 | 73.88 | 4.46 | 53.93 | 2.28 | 27.57 |
| Cold-water-soluble organic matter | 18.46 | 3.49 | 18.91 | 1.82 | 9.86 | 2.18 | 11.81 |
| Hot-water-soluble organic matter | 12.60 | 6.76 | 53.66 | 3.40 | 26.98 | 2.79 | 22.14 |
| Hemicelluloses | 28.83 | 20.93 | 72.54 | 20.59 | 71.39 | 15.83 | 54.91 |
| Celluloses | 30.73 | 20.37 | 66.34 | 16.45 | 53.54 | 11.51 | 37.44 |
| Lignins | 67.56 | 69.23 | 102.47 | 67.39 | 99.75 | 57.41 | 84.97 |
| Crude protein | 4.25 | 10.38 | 244.24 | 9.69 | 228.00 | 9.60 | 225.88 |

TABLE 15

*Total decomposition of the various organic constituents in mature oak leaves, in the presence of added nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | ORGANIC SUBSTANCES LEFT, AFTER DAYS OF DECOMPOSITION | | | | | |
|---|---|---|---|---|---|---|---|
| | | 66 | | 143 | | 386 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | gm. | gm. | | gm. | | gm. | |
| Total dry material | 223.00 | 171.00 | 76.68 | 157.00 | 70.40 | 125.00 | 56.05 |
| Ether-soluble fraction | 8.27 | 4.53 | 54.78 | 2.73 | 33.01 | 0.84 | 10.16 |
| Cold-water-soluble organic matter | 18.46 | 2.74 | 14.84 | 2.26 | 12.24 | 3.58 | 19.39 |
| Hot-water-soluble organic matter | 12.60 | 5.30 | 42.06 | 3.20 | 25.40 | 3.05 | 24.21 |
| Hemicelluloses | 28.83 | 21.53 | 74.63 | 20.83 | 72.20 | 16.56 | 57.44 |
| Celluloses | 30.73 | 20.34 | 66.23 | 17.18 | 55.91 | 11.54 | 37.55 |
| Lignins | 67.56 | 68.48 | 101.36 | 63.66 | 94.23 | 50.44 | 74.66 |
| Crude protein | 4.25 | 11.32 | 266.35 | 10.80 | 254.12 | 10.31 | 242.59 |

and degree of decomposition of the three plant materials lead us to the conclusion that the abundance of nitrogen in the plant residue undergoing decomposition is not the only controlling factor in the rapidity with which microörganisms are capable of attacking it. Actually, the addition of avail-

able nitrogen had no appreciable influence in hastening the decomposition of the leaves, as seen by the reduction in the total organic matter, as well as the celluloses and hemicelluloses.

It has been found, in experiments reported previously (15), that the addition of a small amount of available nitrogen had a decidedly favorable effect upon the decomposition of mature oak leaves, as measured by the evolution of carbon dioxide, the absorption of available nitrogen, and the decomposition of total organic matter, celluloses, and hemicelluloses. The fact, however,

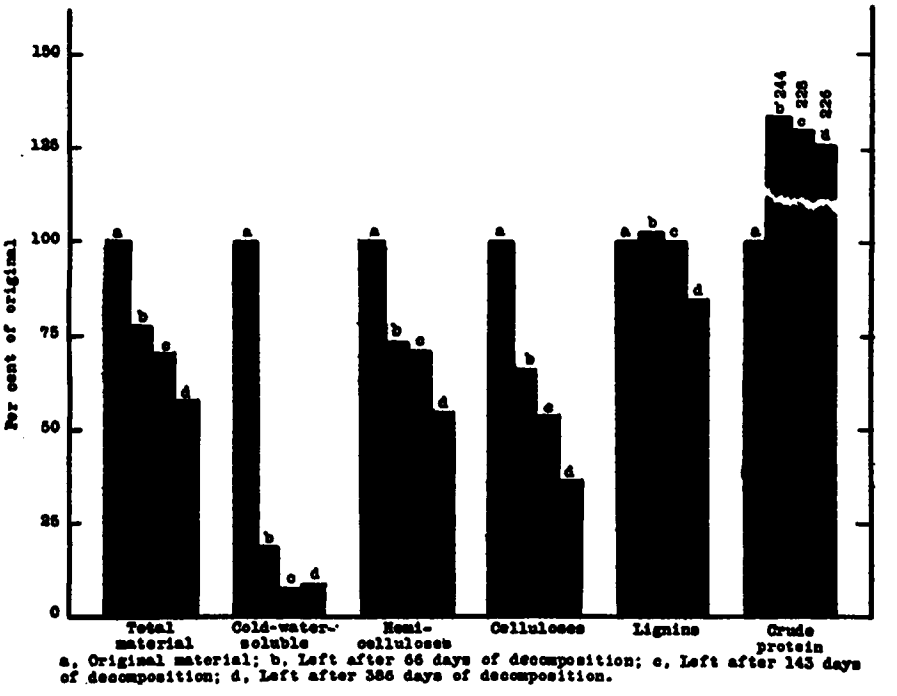


FIG. 5. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF OAK LEAVES WITHOUT ADDITIONAL NUTRIENT SALTS

that in these experiments no such striking differences have been found, do not indicate a possible discrepancy between these two sets of data. The difference is due entirely to the fact that in the previous investigations only a short period of incubation (28 days) was employed; in these studies, however, the first analysis was made only after 68 days of incubation. In other words, even in the case of a plant material with 0.77 per cent nitrogen, the addition of a small amount of available nitrogen will exert a stimulating effect upon its decomposition during the early stages. However, when decomposition has advanced, there will be sufficient nitrogen liberated from the degradation of the plant proteins to take care of the celluloses and hemicelluloses. This

is true especially in the case of a material like oak leaves, the decomposition of which, due to the high lignin, tannin, and wax contents, is considerably delayed, when compared with that of straw and corn stalks. Even in the early periods of incubation, the effect of additional nitrogen upon the decomposition of the oak leaves was considerably less than upon the decomposition of rye straw and corn stalks, as shown in the earlier contribution (15).

Although the water-soluble substances of the oak leaves decomposed very rapidly, the celluloses and hemicelluloses resisted decomposition more than

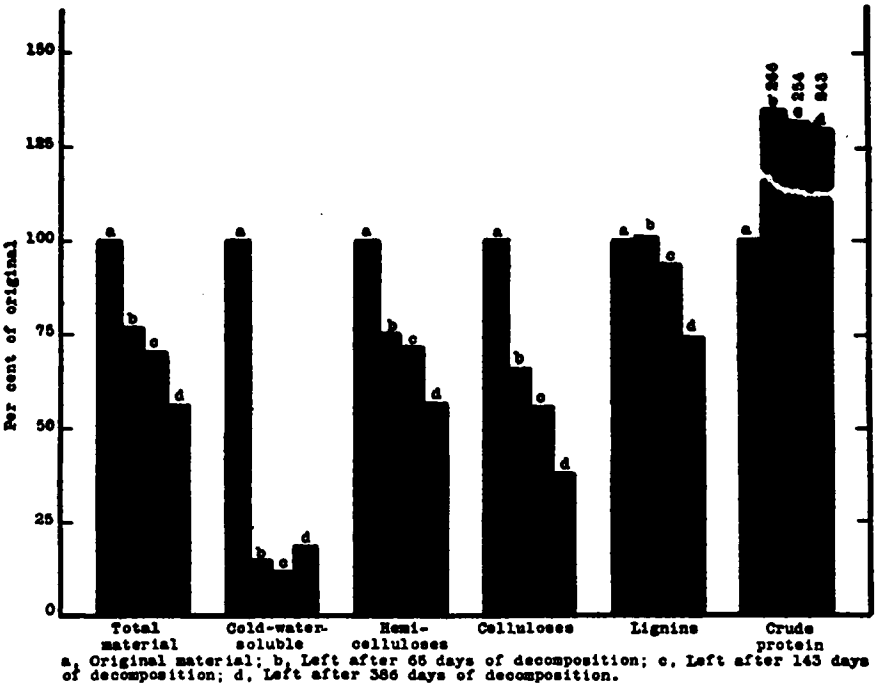


FIG. 6. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF OAK LEAVES WITH ADDITIONAL NUTRIENT SALTS

in the case of the two other plant materials. This is due, not to the lack of the available nitrogen, as found in the case of the rye straw, but to the abundance of the lignins. It has been shown elsewhere (13) that the lignins are not only resistant to decomposition, but they even delay the disintegration of the celluloses. The removal of the lignins from a plant residue hastens the decomposition of the celluloses. In the case of the oak leaves, the lignins remained practically undecomposed, until a year had passed, and only then a small fraction had disappeared, the nature of the change still remaining undetermined.

The crude or water-insoluble proteins have also increased in the case of the

oak leaves. Where nitrogen was added in the form of ammonia, it was changed rapidly into organic nitrogen by the synthetic action of the microörganisms. When no inorganic nitrogen was added, the water-soluble nitrogen compounds disappeared, giving rise to water-insoluble nitrogenous complexes. This is brought out in table 16.

When the results of the decomposition of mature oak leaves are compared with that of green oak leaves, as reported elsewhere (16), marked differences are observed, due entirely to differences in the chemical composition of the two kinds of leaves used in both experiments. The younger leaves were richer in water-soluble constituents and in nitrogen, and poorer in lignins. As a result of these differences, the younger leaves decomposed much more rapidly, large amounts of nitrogen actually becoming liberated in the form

TABLE 16

*Nitrogen transformation in the decomposition of oak leaves*

In per cent of total material

| FORM OF NITROGEN | NO ADDITIONAL NITROGEN | | | | AMMONIUM PHOSPHATE ADDED | | | |
|---|---|---|---|---|---|---|---|---|
| | Incubation | | | | Incubation | | | |
| | 0 days | 66 days | 143 days | 386 days | 0 days | 66 days | 143 days | 386 days |
| Total nitrogen | 0.77 | 1.03 | 1.06 | 1.26 | 0.87 | 1.15 | 1.20 | 1.43 |
| Soluble in cold water | 0.09 | 0.02 | 0.04 | 0.03 | 0.19 | 0.04 | 0.05 | 0.04 |
| Soluble in hot water | Trace | 0.05 | 0.04 | 0.05 | Trace | 0.05 | 0.05 | 0.07 |
| Hydrolizable by 2 per cent HCl | 0.18 | 0.17 | 0.22 | .... | 0.18 | 0.21 | 0.27 | .... |
| "Humin" nitrogen, not acted upon by autoclaving with 6 per cent $H_2SO_4$ | 0.30 | 0.47 | 0.53 | 0.49 | 0.30 | 0.49 | 0.53 | 0.53 |

of ammonia even within a period of six months of decomposition under aerobic conditions.

## DECOMPOSITION OF ALFALFA

The chemical composition of the alfalfa plant used in these experiments differed considerably from that of the other three plant materials. As a representative of the group of leguminous plants, it was characterized by a high nitrogen content, a large part of which was water-soluble. It contained also the largest amount of cold-water-soluble substances, which is the fraction previously found to disappear most rapidly when a plant is undergoing decomposition. The alfalfa also contained the lowest lignin content; this would tend to favor further the ease of its decomposition. One would expect from an analysis of the chemical composition of this material that it should undergo rapid disintegration, especially during the early stages.

It has been shown previously (15), that when a plant material contains about 1.7 per cent nitrogen it undergoes rapid decomposition even when no

additional nitrogen is available. In view of the fact that the alfalfa contained more than this amount of nitrogen, the addition of inorganic nitrogen should not exert any favorable effect upon the rapidity of its decomposition. This was actually found to be the case. The decomposing alfalfa receiving ammonium phosphate and calcium carbonate actually decomposed more

TABLE 17

*Chemical composition of alfalfa at different stages of decomposition, without the addition of nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | | |
|---|---|---|---|---|---|
| | | 27 | 68 | 205 | 405 |
| Ether-soluble | 2.75 | ..... | 1.90 | 0.71 | 0.90 |
| Cold-water-soluble | 12.44 | 12.55 | 11.08 | 9.16 | 11.15 |
| Hot-water-soluble | 4.80 | 5.13 | 7.13 | 6.50 | 6.34 |
| Hemicelluloses | 8.52 | 6.24 | 6.39 | 7.29 | 8.22 |
| Celluloses | 26.71 | 22.63 | 16.48 | 15.15 | 15.90 |
| Lignins | 10.78 | 15.12 | 14.85 | 18.37 | 16.08 |
| Crude protein | 8.13 | 8.43 | 7.31 | 10.31 | 9.18 |
| Ash | 10.30 | ..... | ..... | 23.43 | 24.88 |

TABLE 18

*Chemical composition of alfalfa at different stages of decomposition, with the addition of nutrient salts*

On per cent basis of dry material

| CHEMICAL CONSTITUENTS | ORIGINAL PLANT MATERIAL | AFTER DAYS OF DECOMPOSITION | | | |
|---|---|---|---|---|---|
| | | 27 | 68 | 205 | 405 |
| Ether-soluble | 2.75 | ..... | 2.02 | 1.08 | 0.60 |
| Cold-water-soluble | 12.44 | 10.10 | 10.87 | 8.23 | 9.81 |
| Hot-water-soluble | 4.80 | 4.34 | 5.56 | 5.94 | 6.69 |
| Hemicelluloses | 8.52 | 6.15 | 6.19 | 8.07 | 7.16 |
| Celluloses | 26.71 | 26.00 | 19.31 | 17.22 | 17.55 |
| Lignins | 10.78 | 14.91 | 16.51 | 16.98 | 15.62 |
| Crude protein | 8.13 | 7.94 | 8.50 | 12.25 | 8.56 |
| Ash | 10.30 | ..... | ..... | 25.54 | 27.88 |

slowly than the material not receiving any additional salts. This can be explained as follows: the rapid decomposition of the alfalfa, rich in soluble nitrogen, led to an abundant liberation of ammonia. Because the compost was enclosed in a covered pot, the reaction became alkaline. The addition of ammonium phosphate and calcium carbonate tended to make the reaction even more alkaline, so that the ammonia actually saturated the atmosphere of the compost; this resulted in a considerable depression of many groups of organisms, notably of the fungi and various bacteria. This depression had a

TABLE 19

*Total decomposition of the various organic constituents of alfalfa, without the addition of nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | ORGANIC SUBSTANCES LEFT, AFTER DAYS OF DECOMPOSITION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 27 | | 68 | | 205 | | 405 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | gm. | gm. | | gm. | | gm. | | gm. | |
| Total dry material | 260.00 | 181.00 | 70.00 | 151.80 | 58.40 | 119.10 | 45.80 | 100.00 | 38.50 |
| Ether-soluble fraction | 7.15 | ..... | ..... | 2.88 | 40.28 | 0.85 | 11.89 | 0.90 | 12.59 |
| Cold-water-soluble organic matter | 32.34 | 22.72 | 70.25 | 16.82 | 52.01 | 10.91 | 33.74 | 11.15 | 34.48 |
| Hot-water-soluble organic matter | 12.48 | 9.29 | 74.44 | 10.82 | 86.70 | 7.74 | 62.02 | 6.34 | 50.80 |
| Hemicelluloses | 22.16 | 11.29 | 50.94 | 9.70 | 43.77 | 8.68 | 39.17 | 8.22 | 37.09 |
| Celluloses | 69.45 | 40.95 | 58.96 | 25.02 | 36.03 | 18.04 | 25.98 | 15.90 | 22.89 |
| Lignins | 28.02 | 27.37 | 97.68 | 22.54 | 80.44 | 21.88 | 78.09 | 16.08 | 57.39 |
| Crude protein | 21.14 | 15.27 | 72.23 | 11.10 | 52.51 | 12.28 | 58.09 | 9.18 | 43.42 |

TABLE 20

*Total decomposition of the various organic constituents of alfalfa, with the addition of nutrient salts*

| ORGANIC CONSTITUENTS | ORIGINAL MATERIAL | ORGANIC SUBSTANCES LEFT, AFTER DAYS OF INCUBATION | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | 27 | | 68 | | 205 | | 405 | |
| | | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original | Total residue | Per cent of original |
| | gm. | gm. | | gm. | | gm. | | gm. | |
| Total dry material | 260.00 | 207.00 | 79.62 | 151.89 | 58.40 | 116.00 | 44.50 | 109.80 | 42.20 |
| Ether-soluble fraction | 7.15 | ..... | ..... | 3.07 | 42.94 | 1.25 | 17.48 | 0.66 | 9.23 |
| Cold-water-soluble organic matter | 32.34 | 20.71 | 64.04 | 16.51 | 51.05 | 9.55 | 29.53 | 10.77 | 33.30 |
| Hot-water-soluble organic matter | 12.48 | 8.90 | 71.31 | 8.44 | 67.63 | 6.89 | 55.21 | 7.35 | 58.89 |
| Hemicelluloses | 22.16 | 12.60 | 56.86 | 9.40 | 42.42 | 9.36 | 42.24 | 7.86 | 35.47 |
| Celluloses | 69.45 | 53.30 | 76.75 | 29.32 | 42.22 | 19.98 | 28.77 | 19.27 | 27.75 |
| Lignins | 28.02 | ..... | ..... | 25.07 | 89.47 | 19.70 | 70.31 | 17.15 | 61.21 |
| Crude protein | 21.14 | 16.28 | 77.01 | 12.91 | 61.07 | 14.21 | 67.22 | 9.40 | 44.47 |

marked effect upon the rapidity of decomposition of some of the organic complexes in the alfalfa, especially of the celluloses.

Tables 17 and 18 give the chemical composition of the alfalfa at the different stages of decomposition. Analyses were made after 27, 68, 205, and 405 days of incubation at 25–27°C. Tables 19 and 20 and figures 7 and 8 give the total amounts of the various chemical constituents in the residual matter, at the different periods of incubation.

A comparison of the rapidity of decomposition of corn stalks, rye straw, and alfalfa, as measured by the evolution of carbon dioxide, has shown (15)

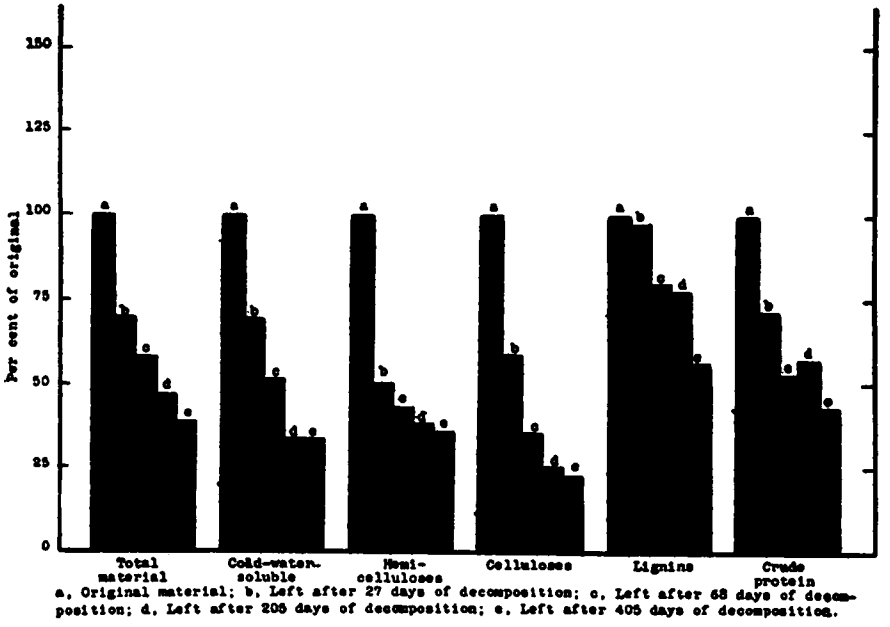


FIG. 7. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF ALFALFA WITHOUT ADDITIONAL NUTRIENT SALTS

that the alfalfa decomposed far more rapidly than did the other two materials. However, when a long period of incubation is used, the alfalfa is found to leave a considerably larger amount of residual material than do the corn stalks. This is due primarily to the artificial conditions under which these studies were carried out. The rapid accumulation of ammonia as a result of the protein decomposition in the nitrogen-rich alfalfa prevented a rapid development of the fungi and various bacteria, which accounts for the larger amount of celluloses and hemicelluloses that remained undecomposed than in the case of the corn stalks.

The lignins of the alfalfa were also more resistant to decomposition than the other organic complexes. Although the relative protein content of the

compost tended to increase with the advance of decomposition, especially within the first 205 days, the total protein content diminished rapidly. This

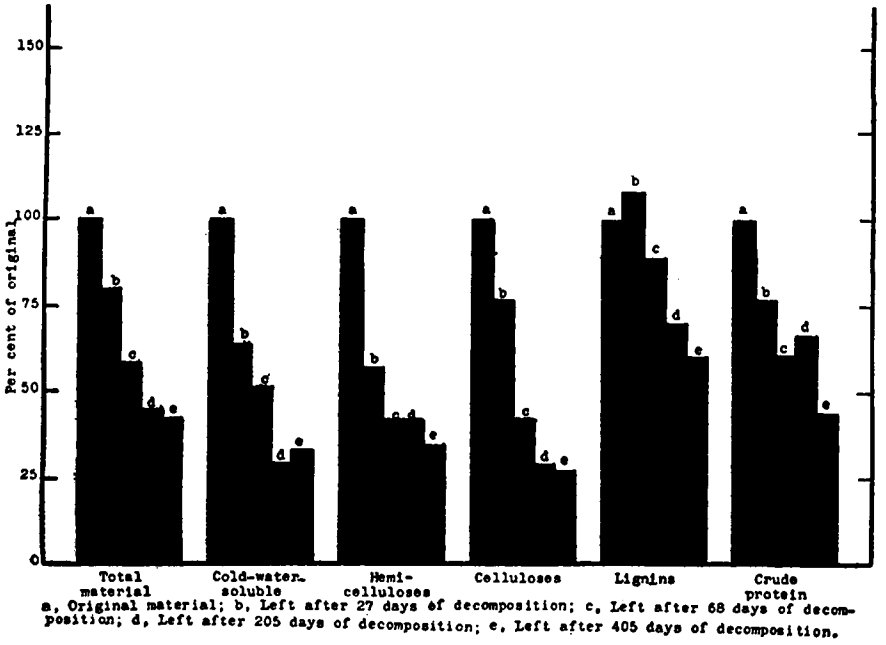


FIG. 8. DECOMPOSITION OF VARIOUS CHEMICAL CONSTITUENTS OF ALFALFA WITH ADDITIONAL NUTRIENT SALTS

TABLE 21

*Nitrogen transformation in the aerobic decomposition of alfalfa*

In per cent of total material

| FORM OF NITROGEN | NO ADDITIONAL NITROGEN | | | | | AMMONIUM PHOSPHATE ADDED | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Incubation | | | | | Incubation | | | | |
| | 0 days | 27 days | 68 days | 205 days | 405 days | 0 days | 27 days | 68 days | 205 days | 405 days |
| Total nitrogen | 2.58 | 2.63 | 2.70 | 2.60 | 2.40 | 2.66 | 2.32 | 2.47 | 2.80 | 2.32 |
| Ammonia nitrogen | 0 | 0.39 | 1.66 | .... | .... | 0.08 | 0.51 | 1.68 | .... | .... |
| Soluble in cold water | 0.93 | 0.98 | 0.78 | 0.57 | 0.61 | 1.01 | 0.79 | 0.75 | 0.59 | 0.65 |
| Soluble in hot water | 0.35 | 0.30 | 0.39 | 0.38 | 0.32 | 0.35 | 0.26 | 0.36 | 0.35 | 0.30 |
| Hydrolizable in 2 per cent HCl | 0.59 | 0.38 | 0.47 | .... | 0.62 | 0.59 | 0.37 | 0.51 | .... | 0.57 |
| "Humin" nitrogen, not acted upon by autoclaving with 6 per cent $H_2SO_4$ | 0.37 | 0.45 | 0.41 | 0.39 | 0.34 | 0.37 | 0.42 | 0.49 | 0.47 | 0.38 |

is the opposite of what has taken place in the case of the other three plant materials and is due to the initial high protein content of the alfalfa. This is brought out in table 21. The total nitrogen remained at about the same

level, whereas the water-soluble nitrogen disappeared only partly. There was also no marked accumulation of proteins readily hydrolizable by dilute (2 per cent) hydrochloric acid and of the non-hydrolyzable, so-called "humin" nitrogen. These facts are again distinctly different from those which have been found in the case of the nitrogen-poor plant materials.

## DISCUSSION

An analysis of the data dealing with the decomposition of four different plant materials, varying markedly in origin and in chemical composition, brings out some illuminating facts. These can be summarized as follows: *the rapidity and nature of decomposition of plant residues under aerobic conditions depend primarily upon the chemical composition of the particular plant materials.*

Among the various chemical constituents of the plant materials which may influence their decomposition, the following deserve careful consideration:

1. The amount and nature of the constituents which are soluble in cold water.
2. The abundance of the celluloses and hemicelluloses.
3. The amount and nature of the nitrogenous complexes.
4. The abundance of the lignins.

The greater the amount of water-soluble material in a plant residue the more rapid will be its decomposition, especially during the early stages. This is easy to understand, since the water-soluble fraction comprises the simple sugars, amino acids, soluble salts,—substances all readily used by a great number of microörganisms, both fungi (especially the Phycomycetes) and bacteria (especially the spore-forming organisms). The younger a plant is, the higher is its content of water-soluble substances. The decrease in the rapidity of decomposition with the increase in age of plant is due, among other factors, to a decrease in this group of plant constituents. Further, the decomposition of sugars, organic acids, and other water-soluble organic complexes can be carried on in the soil by both aerobic and anaerobic bacteria, which are capable of using gaseous atmospheric nitrogen; hence, the amount and availability of the nitrogen are not controlling factors in the decomposition of these organic materials.

The most abundant groups of constituents in the various plant residues which undergo decomposition in the soil or in manure are the celluloses and hemicelluloses. Usually they make up about 50 to 65 per cent of the sum total of the dry plant material. Their decomposition is carried out by certain groups of fungi and specific bacteria. These organisms synthesize considerable cell substance in the process of decomposition of the celluloses. For this purpose a certain amount of available nitrogen is required. Hence the decomposition of the celluloses and hemicelluloses depends upon the presence of organisms capable of decomposing them and upon the amount of available nitrogen.

The celluloses are usually not present in the plant residues in a free condition but are combined largely with lignins, in the form of ligno-celluloses. Whether the combination is chemical or physical in nature, the presence of lignin markedly influences the ability of the microörganisms to decompose the celluloses. The various chemical treatments which have in view an increase of digestibility by animals of plant residues high in lignins consist in the partial dissolution of the lignins. The lignins themselves are decomposed by microörganisms (with certain few exceptions, as in the case of some wood-destroying Hymenomycetes) only to a very limited extent, even under aerobic conditions. A long time may elapse before any measurable reduction in the lignins will be observed.

It must be kept in mind that the decomposition processes taking place in these studies were carried out at an optimum temperature and moisture; the conditions were also favorable for the activities of aerobic organisms. But even under these conditions, the decomposition of the lignins has been very limited in comparison with that of the celluloses and other organic complexes. In the case of the corn stalks with nutrients, there was left, after 405 days of decomposition, 20.30 per cent of the total organic matter, 3.83 per cent of the cellulose, and 42.49 per cent of the lignin. In the case of the rye straw, there was left, after 386 days incubation, 55.23 per cent of the total organic matter, 37.28 per cent of the cellulose, and 69.61 per cent of the lignin. In the case of the oak leaves, there was left, after 386 days decomposition, 56.05 per cent of the total organic matter, 37.55 per cent of the cellulose, and 74.66 per cent of the lignin. In the case of the alfalfa, there was left, after 405 days of decomposition, 42.20 per cent of the total organic matter, 27.75 per cent of the cellulose, and 61.21 per cent of the lignin. In other words, all the four plant materials, obtained from different sources and varying markedly in chemical composition, behaved alike as far as the lignins were concerned. The reduction of the lignins was considerably less than that of the total plant residues and much less than any of the other organic plant constituents.

The behavior of the nitrogen complexes deserves also special consideration. The rapid increase in the protein content as a result of the decomposition of plant residues with a low nitrogen content has been definitely established. That this protein is a result of the synthesizing activities of the microörganisms and that a definite ratio exists between the amount of cellulose decomposed and the nitrogen transformed from an inorganic into an organic form has been amply demonstrated previously. On the other hand, the results on the decomposition of alfalfa, a plant residue with a nitrogen content greater than 1.7 per cent, showed a decrease of the total protein, although accompanied at the same time by an increase in the relative nitrogen content of the decomposing material. In other words, even in the case of a protein-rich plant material, the processes of decomposition were accompanied by synthesis of new proteins, so that the nitrogenous complexes which resulted

from the decomposition of the alfalfa are of an entirely different nature from the original plant proteins.

Among the other organic constituents of the plant residues undergoing decomposition, the hot-water-soluble fraction deserves some consideration. This fraction has decreased to a less extent than many of the other groups of plant complexes. It is quite distinct from the cold-water-soluble fraction in that it is reduced much less rapidly than the latter. This is due to two factors: (*a*) Hot water extracts certain complexes, like the tannins, which are quite resistant to decomposition; (*b*) the microörganisms synthesize various substances soluble in hot water but not in cold water.

The ether-soluble fraction comprises also a heterogeneous group of complexes, including various oils, fats, waxes, and sterols. Some of these decompose quite rapidly, whereas others are very resistant to decomposition. This is largely the reason why the ether-soluble fraction of alfalfa or corn stalks decomposed readily whereas that of the straw proved to be much more resistant to decomposition.

## SUMMARY

1. The decomposition of four plant materials; namely, corn stalks, rye straw, oak leaves, and alfalfa plants, has been studied under aerobic conditions, in the presence of an optimum amount of moisture and at 25–27°C.

2. The processes of decomposition have been followed by determining the disappearance of the total organic matter as well as of the more important groups of organic complexes.

3. The nature and rapidity of decomposition of different plant materials are markedly influenced by their chemical composition, provided the conditions for decomposition are the same.

4. The decomposition of the sugars, celluloses, hemicelluloses, fats, and proteins account for most of the decomposed plant materials.

5. The lignins are more resistant to decomposition and tend, therefore, to accumulate. Under aerobic conditions, however, there is a decided reduction in the total lignin content, indicating that, although it is attacked less readily than the celluloses and proteins, its resistance to decomposition is only relative.

6. In the case of plant materials with a low nitrogen content (0.2 to 1.7 per cent), the decomposition of the organic matter is accompanied by a relative and absolute increase in the crude protein content. This is due to the synthesizing activities of the microörganisms, which obtain their energy from the decomposition of the celluloses and hemicelluloses.

7. The celluloses and hemicelluloses, including the pentosans, disappear more rapidly than can be accounted for by the reduction in total organic matter. This is balanced by the accumulation of the lignins and proteins.

8. Among the other synthesized products, the hemicelluloses occupy a prominent place. This is partly accounted for by the fact that, although the pentosans comprising most of the hemicelluloses in the plant material begin

to decompose more rapidly than the celluloses, toward the end of decomposition there is left more hemicellulose than cellulose.

9. The addition of available inorganic nitrogen salt hastens the decomposition of celluloses and hemicelluloses, hence of those plant materials which are rich in celluloses and hemicelluloses and poor in proteins.

10. The residues left, after the plant materials have decomposed for a period of 12 to 14 months at an optimum temperature and moisture and under aerobic conditions, possess all the properties of soil organic matter or soil "humus." This is true especially of the corn stalks which have undergone most rapid decomposition.

11. This residual organic matter or "humus" is made up chiefly of lignins or modified lignin complexes largely of plant origin, of proteins and other complex organic nitrogenous compounds largely of microbial origin, of hemicelluloses partly of plant and partly of microbial origin, of a small amount of celluloses undergoing decomposition, and of varying concentrations of a number of different other organic complexes either in the process of decomposition, resistant to decomposition, or products of decomposition.

12. This residual material or "humus" is not in a state of equilibrium but undergoes continuous change, the rate of change becoming constantly slower, approaching that of the soil "humus."

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